

## **Using NOGAPS Singular Vectors to Diagnose Large-scale Influences on Tropical Cyclogenesis**

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### **LONG-TERM GOALS**

The overarching goal is to improve our understanding of synoptic-scale influences on tropical cyclone (TC) formation and motion in the western North Pacific Ocean, in the context of error growth in forecast models. Benefits to the Navy would include improved forecast skill of the structure and track of developing and recurving TCs.

### **OBJECTIVES**

The first objective is to connect Singular Vector (SV) and ensemble perturbation growth to synoptic-scale dynamical influences on tropical cyclone formation and structure change. The second objective is to extend these investigations towards vortex initialization and analysis of tropical cyclone structure

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in high-resolution models. The goal is to extend these methodologies into the Navy's COAMPS-TC framework.

## **APPROACH**

Several sensitivity and predictability studies have been completed. The approach has been to investigate perturbation growth in SVs and in ensemble predictions, for cases from ONR's Tropical Cyclone Structure (TCS-08) field experiment.

The sensitivity patterns, evolving horizontal and vertical structure and error growth associated with SVs have been investigated. The connection between perturbation structures and synoptic-scale processes influencing TCs has been explored. Hypotheses for SV growth have been formulated and published by Munehiko Yamaguchi, the graduate student funded on this grant, using a barotropic model with idealized vortices and initial conditions from the TCS-08 case of Typhoon Sinlaku.

A highly configurable vortex initialization method based on theory and observations has been designed to provide superior representations of initial TC structure in high-resolution models than are presently achievable via data assimilation. The 2-km resolution version of the Weather Research and Forecasting (WRF) model is presently being used for this purpose, and plans are underway to transfer this code to the COAMPS-TC framework in the coming year. A manuscript on this method and the sensitivity of numerical simulations to the prescribed initial vortex is in preparation.

## **WORK COMPLETED**

After completing two publications in 2010 (Majumdar and Finocchio 2010, Yamaguchi and Majumdar 2010), the past year of research has focused on two areas.

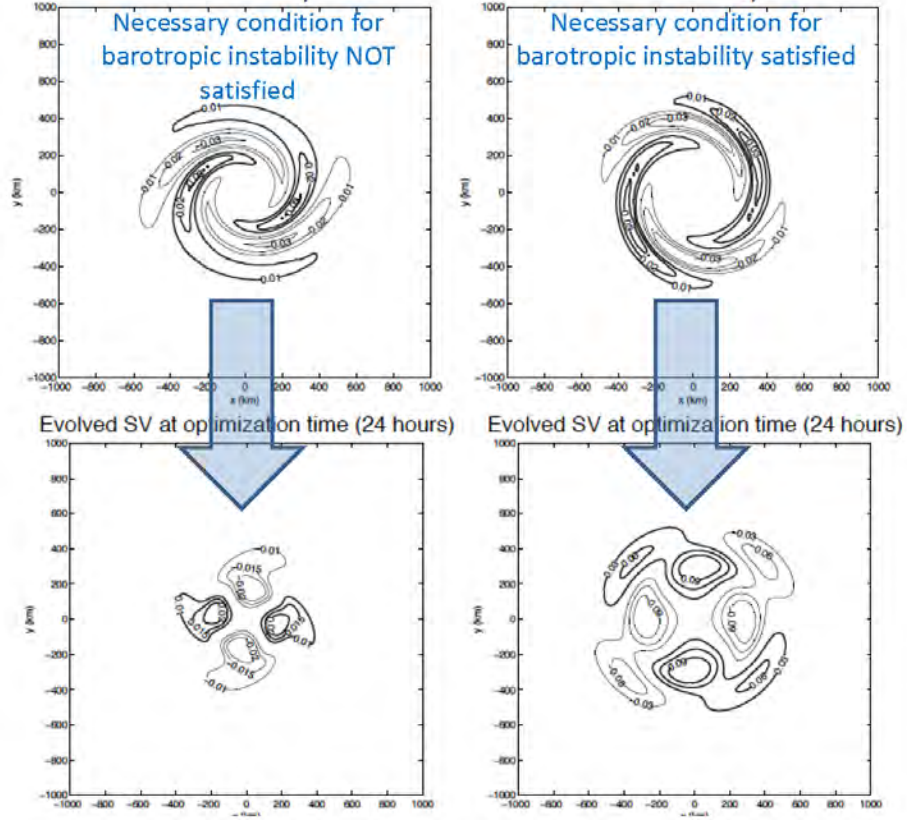
The first is an assessment of the fundamental properties of SVs in TC-like vortices, using a barotropic model. It has been hypothesized that the structures and locations of SVs would be dependent on (i) initial profiles of the vortex, (b) the optimization time interval over which the SVs grow, (iii) the norm by which the SV growth is optimized and (d) the resolution of the model. And, most crucially, the hypothesis that SVs are dependent on the barotropic instability condition in the initial vortex has been tested. A paper is in press in *J. Atmos. Sci.* (Yamaguchi et al. 2011). We expect that the results produced from this study are important in determining processes associated with error growth in more sophisticated models such as COAMPS-TC, and this work will begin shortly.

Second, the configurable framework for vortex initialization has been developed. The rationale is to provide a vortex initialization scheme for use by the broad community, and to offer a benchmark upon which high-resolution data assimilation schemes must improve upon. Software to remove the vortex, similar to the operational version at the Geophysical Fluid Dynamics Laboratory (GFDL, Kurihara et al. 1995), has been completed, together with different configurations of the radial and vertical structure of the vortex comprising a primary and secondary circulation.

## **RESULTS**

In the barotropic model framework, numerical experiments were first computed on an f-plane for initial vortices that did and did not meet the necessary condition for barotropic instability (i.e. the radial gradient of vorticity changes sign at some radius). When the barotropic instability condition is

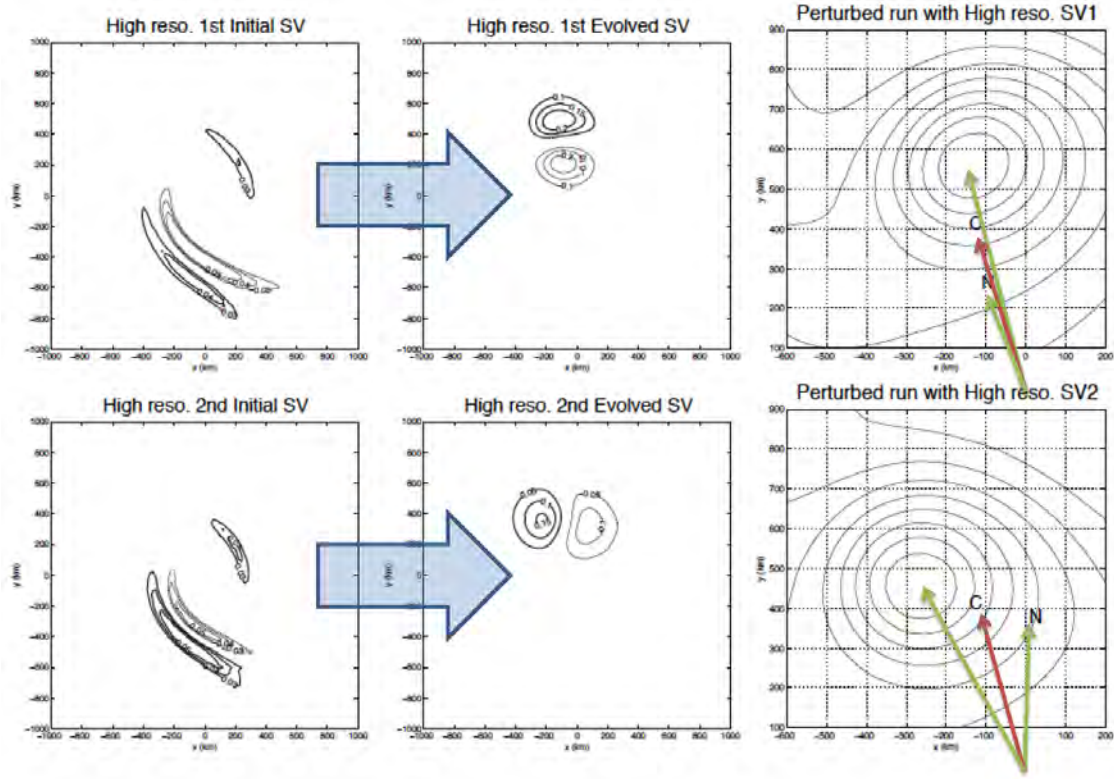
not met, the SVs are tilted against the shear, and grow via the Orr mechanism. The leading singular value increases as the maximum wind is increased, and the location of the SVs moves outward as the radius of maximum wind is increased. When the barotropic instability condition is met, the SVs again are initially tilted against the shear, but only for a transient period. The SVs then lock into a normal mode structure and grow exponentially (Fig. 1).



**FIGURE 1. Left: Time evolution of azimuthal wavenumber two SVs (vorticity fields) on an  $f$ -plane, when the necessary condition for barotropic instability is not satisfied. Right: As for the left panel, but for when the necessary condition for barotropic instability is satisfied.**

*From Yamaguchi et al. (2011).*

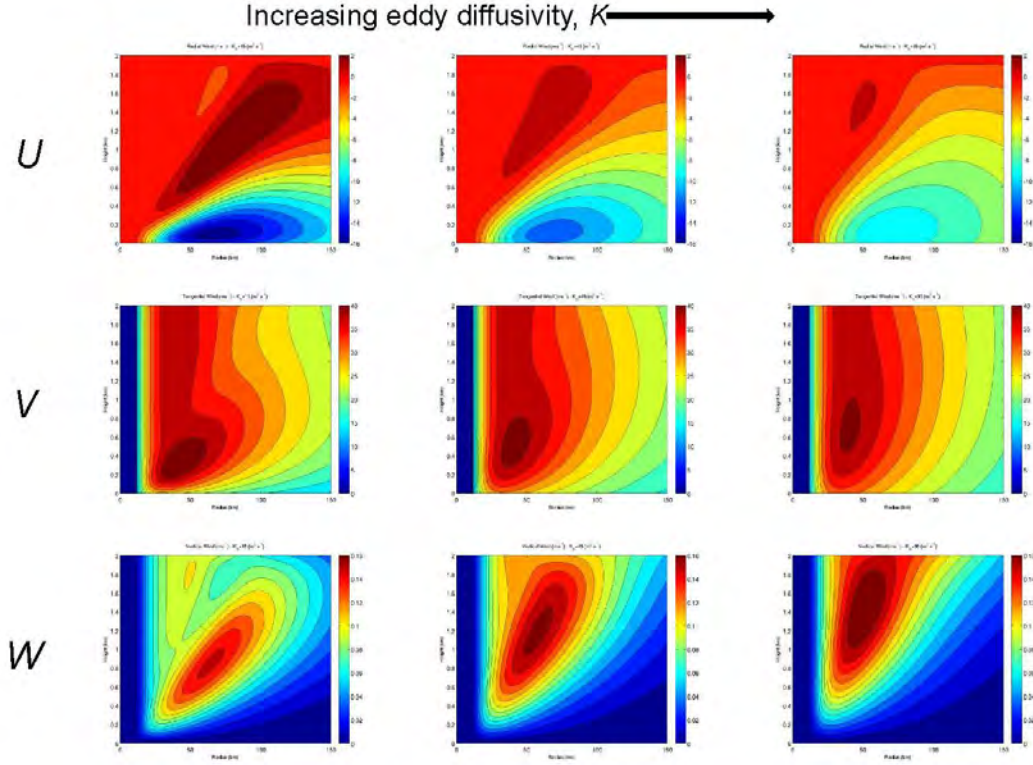
The study was extended to a beta-plane, with the initial conditions created from analysis fields of TCS-08 event Typhoon Sinlaku (2008). It was found that the 1<sup>st</sup> and 2<sup>nd</sup> SVs are initially very asymmetric, and that they grow into a wavenumber 1 structure at the optimization time. We therefore suggest that these leading 2 SVs capture the along-track and cross-track errors of the TC. A minor dependence on the resolution was evident, but not enough to suggest that the resolution of SVs in complex models (such as NOGAPS) heavily compromises their utility for predictability studies and targeting (Fig. 2).



**FIGURE 2.** *Left: Initial SVs (vorticity fields). Middle: Evolved SVs (vorticity fields). Right: Vorticity fields of 24-h numerical integrations where the initial SVs are used as the initial perturbation for the analysis of Typhoon Sinlaku (2008). The optimization time is 24 hours. The ‘C’ and ‘N’ on the right figures represent the cyclone center of the non-perturbed and two perturbed runs with an opposite sign of SVs, respectively. From Yamaguchi et al. (2011).*

For the vortex initialization study, radial profiles based on a modified Rankine vortex and on a profile fit to historical observations (Willoughby et al. 2006) have been introduced for the primary circulation. These profiles can be constructed based on any observations of the maximum azimuthal wind and its radius. For the secondary circulation, a realistic three-dimensional boundary layer structure has been introduced, based on the work of an ONR-funded PI Ralph Foster (University of Washington) (Foster 2009). Configurable parameters include the boundary layer height and eddy diffusivity (Fig. 3). In the free troposphere, the vertical structure of the axisymmetric tangential wind is based on a thermal wind balanced, moist neutral steady state model (Emanuel 1986). Conservation of angular momentum in the boundary layer is exploited to match the flow between the boundary layer and the free troposphere.

Numerical observation system simulation experiments are underway, in which a ‘nature run’ has been developed for a realistic long-lived TC. The fidelity of the configurable vortex in producing accurate analyses and predictions of the TC structure with respect to the nature run is presently under investigation. The vortex framework with the primary and secondary circulations is nearly ready for transition to Navy collaborators.



**FIGURE 3.** *Vertical cross-sections of Radial ( $u$ ), azimuthal ( $v$ ) and vertical ( $w$ ) components of wind in the boundary layer, for increasing values eddy diffusivity. The radius ( $x$ -axis) extends from 0 to 150 km, and the altitude ( $y$ -axis) extends from the surface to 2 km. The formulation is from Foster (2009).*

## IMPACT/APPLICATIONS

The scientific impact will be an improved understanding of the underlying environmental mechanisms that influence tropical cyclone evolution. This understanding will be coupled with a quantitative knowledge of error growth in global models, via SVs and ensembles. The SVs also possess practical value in that they can be used in future targeting applications. High-resolution simulations, vortex initialization and examination of perturbation growth will be performed in collaboration with the COAMPS-TC team at NRL Monterey, leading to improved Navy forecasts of TC structure.

## TRANSITIONS

A preliminary version of the vortex configuration framework is being used by Dr William Lewis at the University of Wisconsin, for his own vortex initialization and assimilation studies. A more mature version will be available for transition to NRL Monterey within the forthcoming year.

## RELATED PROJECTS

This project is related to that funded by the TCS-08 grant N000140810251: “Advanced Satellite-Derived Wind Observations, Assimilation, and Targeting Strategies during TCS-08 for Developing Improved Operational Analysis and Prediction of Western North Pacific Tropical Cyclones”, on which Majumdar is a Co-PI. The NOGAPS Singular Vectors are also investigated in this grant. The high-resolution modeling and vortex initialization tools developed as part of this project are being used in the collaborative NOPP grant between the PI and CIMSS Wisconsin, NRL Monterey and NCAR, on assimilating satellite data to improve forecasts of TC intensity change.

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## HONORS/AWARDS/PRIZES

The PI has recently been elected a Fellow of the Cooperative Institute of Marine and Atmospheric Science (CIMAS), starting 2011.

The PI has been elected to the WMO THORPEX Data Assimilation and Observing Strategies Working Group (to be confirmed by WMO in September 2011).